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Yagyu

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- (54) DIRECT COMPARISON ADAPTIVE HALTING DECODER AND METHOD OF USE
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- (58) Field of Search 714/755, 794, 714/819

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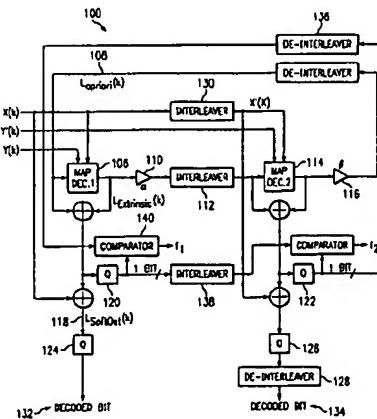
Primary Examiner—Stephen M. Baker

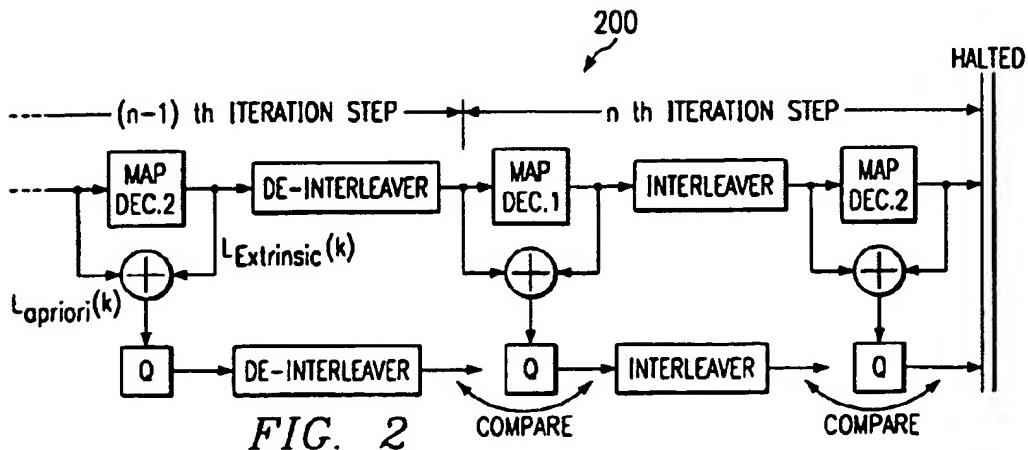
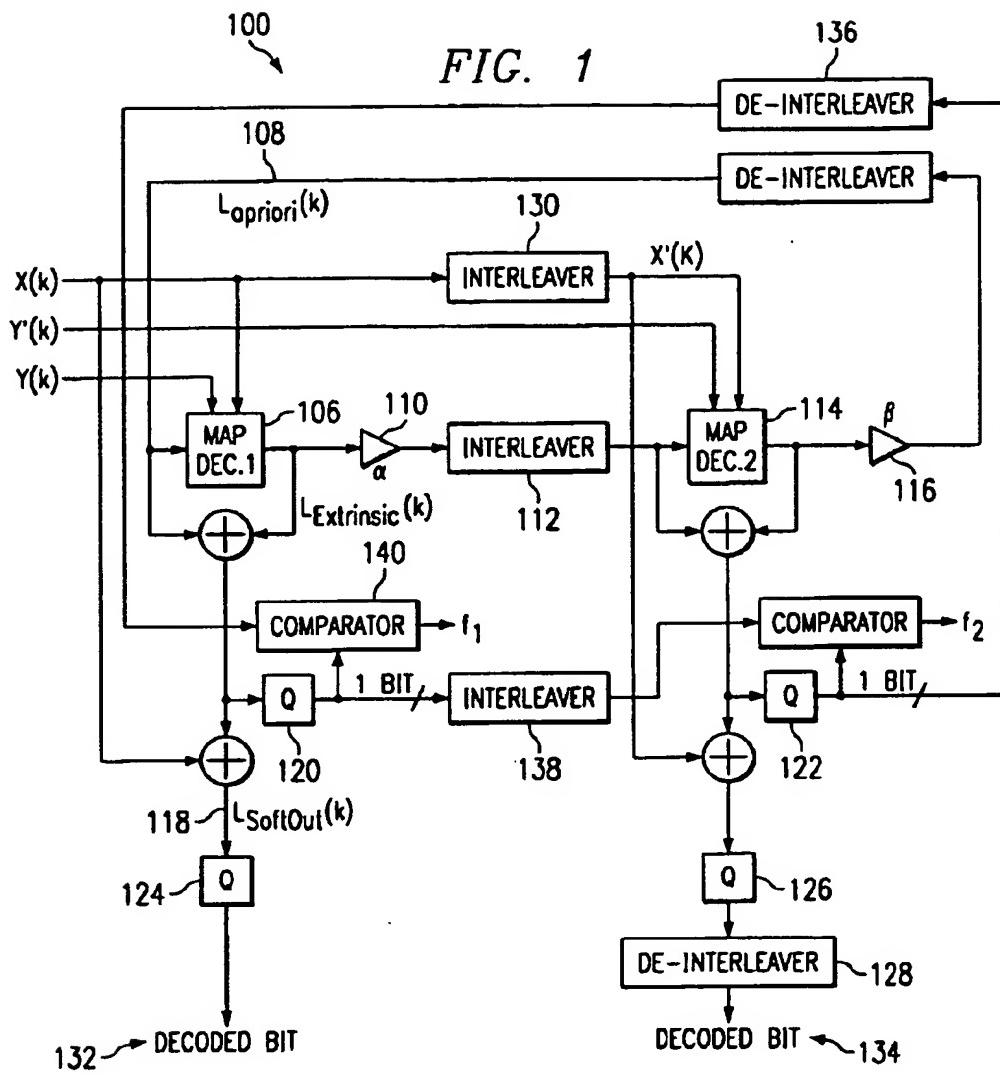
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(57) ABSTRACT

A direct comparison adaptive halting turbo decoder computes the sum of the a priori and the extrinsic information sequences at each iteration step. The sum sequences are coded so as to be simple binary sequences. New sum sequences are generated during each iteration and used to estimate the state of the convergence without resorting to use of transmitted error detection codes. The adaptive halting turbo decoder is halted when the sum sequences generated in a single iteration step produce identical binary sequences, i.e. a change in the sum sequence is observed during the iteration and when there is no more change, the iteration is halted.

29 Claims, 2 Drawing Sheets





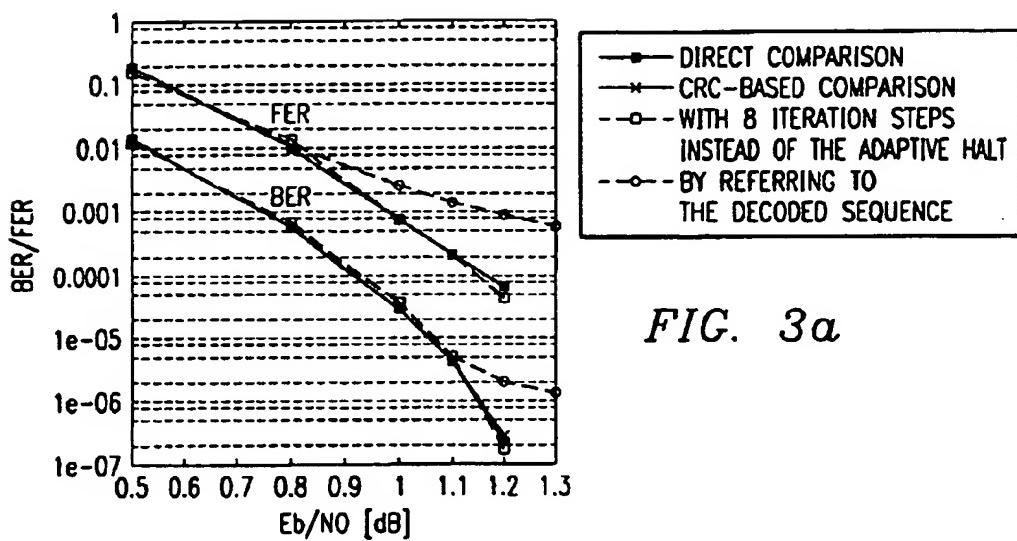


FIG. 3a

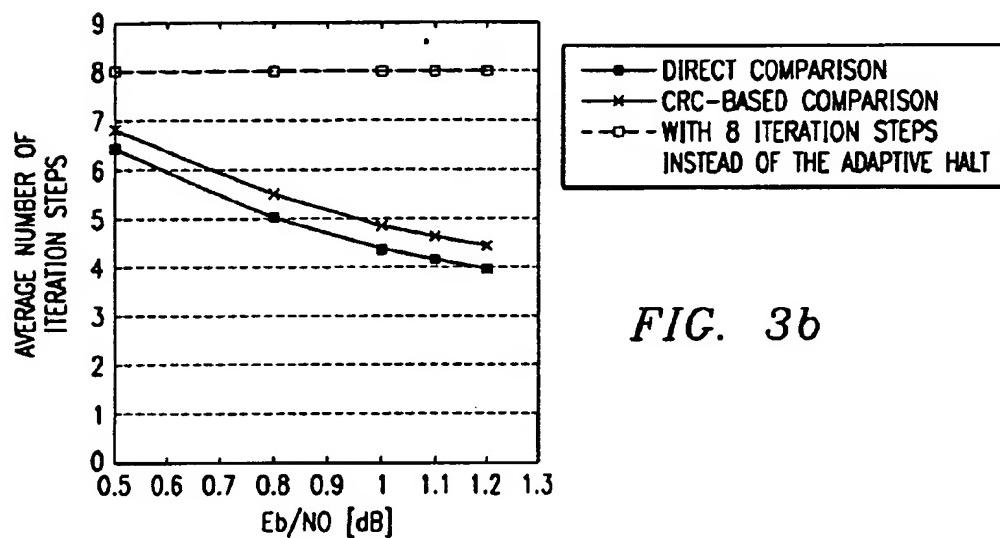


FIG. 3b

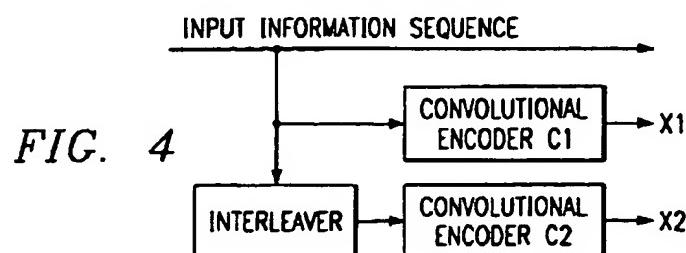


FIG. 4

**DIRECT COMPARISON ADAPTIVE
HALTING DECODER AND METHOD OF USE**

RELATED PATENT APPLICATION

This application is related to co-filed U.S. patent application entitled CRC-based Adaptive Halting Decoder and Method of Use, application Ser. No. 09/547,815.

BACKGROUND OF THE INVENTION

1. **Field of the Invention** This invention relates generally to iterative turbo decoding, and more particularly to adaptive halting algorithms that reduce computational complexity of iterative turbo decoders.

2. **Description of the Prior Art**

Turbo code is well known computational tool that was proposed in 1993 and that attracted the attention of researchers and developers, especially in the art of communication engineering. C. Berrou, A. Glavieux, and P. Thitimajshima, Near Shannon Limit Error-correcting Coding and Decoding: Turbo Codes (I), Proc.ICC '93, pp. 1064-1070, May 1993. The Berrou et al. reference is incorporated by reference herein. A turbo encoder is composed of two recursive systematic convolutional (RSC) encoders and an interleaver to generate the interleaved version of an input information sequence. The interleaved sequence is also encoded using one of the RSC encoders. The resultant turbo code, using parallel concatenation of the two RSC codes, has a substantially large free Hamming distance and therefore provides a powerful error correcting code. The aforesaid Hamming distance can be further improved by employing long interleavers at the expense of larger memory capacity.

FIG. 4 is a simplified block diagram of a parallel-concatenated rate 1/3 turbo encoder. A parallel-concatenated turbo encoder has two or more component encoders in conjunction with one or more interleavers. A component encoder C1 to create a parity sequence X1 encodes an input information sequence. The input information sequence is interleaved and then encoded by C2 to create a second parity sequence X2. The information sequence and the two parity sequences are then multiplexed to create a coded sequence.

The foregoing two RSC codes are alternately MAP-decoded in the turbo decoder, and the reliability of the soft output of the MAP decoder is iteratively updated. The sign of the soft output is improved as a decoded output following a sufficient number of iteration steps. The amplitude of the soft output gradually increases during the iteration process. However, the sign generally remains constant after several iteration steps. Thus, it is easy to recognize a decoded output can become error-free in just a few iteration steps for low-noise channels having a channel-decoded bit error rate (BER) as low as 10^{-6} . Detection of an error-free decoded sequence can significantly reduce computational complexity since the iteration process can then be halted without requiring further iteration computations.

A transmitted sequence is generally encoded with an error detection code such as the familiar cyclic redundancy check (CRC) code disclosed by S. Lin and D. J. Costello Jr., *Error Control Coding: Fundamentals and Applications*, Prentice Hall, N.J., 1983, and incorporated herein by reference. The above error-free decoding can then be checked for accuracy at the receiver side using the CRC code; and when error-free decoding is detected during an iteration, the remaining portion of the iteration can either be ignored or completely halted. A. Shibusaki, H. Suda, and F. Adachi, *Decoding complexity Reduction On Turbo-CRC Concatenated Code in*

W-CDMA Mobile Radio, Proc IEICE General Conf., B-5-109, vol. 1, pp. 541, March 1999 (in Japanese), and incorporated by reference herein, have shown the effectiveness of the foregoing iterative turbo decoding process.

If a transmitted sequence is not encoded with the CRC code, the foregoing technique of Shibusaki et al. cannot be applied however. Even if the transmitted sequence is encoded with the CRC code, the associated receiver decoder must a priori know the generator polynomial of the CRC code and the position of its redundancy check words in the received sequence. This limitation makes the design of the decoder complicated for variable rate data communications.

In J. Hagenauer, E. Offer, and L. Papke, *Iterative Decoding of Binary Block and Convolutional Codes*, IEEE Trans. Inf. Theory, vol. 42, pp. 429-445, March 1996 and in U.S. Pat. No. 5,761,248, entitled Method and Arrangement for Determining an Adaptive Abort Criterion in Iterative Decoding of Multi-dimensionally Coded Information, by J. Hagenauer and F. Burkert, issued June 1998, both references incorporated herein by reference, Hagenauer et al. have shown implementation of the adaptive halting algorithm without resorting to use of the transmitted CRC code. The adaptive halting algorithm of Hagenauer et al. makes use of the difference sequence between two soft output sequences determined at the iteration step as well as the preceding iteration step and derived at each iteration step. Then the L_2 norm of the difference sequence (cross entropy of the two soft output sequences) is calculated at each iteration step. Once the cross entropy of the two soft output sequences becomes less than a predetermined threshold value, the iteration process is halted. Although the techniques developed by Hagenauer et al. do not require use of the transmitted CRC code, the technique otherwise requires an extra large memory capacity to store the soft output sequence data at each preceding iteration step. This is so since the soft output sequence of a typical turbo decoder is very long and therefore has soft output symbols with long word lengths. Further, the aforementioned cross entropy needs to be computed using high accuracy in order to accurately detect the convergence of iterative decoding, which significantly increases the hardware size of the multiplier used for the calculation of the L_2 norm.

P. Robertson, *Illuminating the Structure of Parallel Concatenated Recursive Systematic (TURBO) Codes*, Proc. GLOBECOM'94, pp. 1298-1303, November 1994, incorporated by reference herein, proposes application of the adaptive halting algorithm using the variance of the soft output sequence as the halting criterion. Although the Robertson technique does not require an extra large memory capacity or a large multiplier such as required when using the foregoing cross entropy computation methods, the technique of Robertson nonetheless requires additional multiplier hardware to calculate the variance. The requirement for a multiplier is disadvantageous for low power and low-cost silicon implementations since the additional hardware will increase both the size and power requirements necessary to implement the adaptive halting algorithm.

In view of the foregoing, a need exists in the communication art for an adaptive halting structure and method that does not require use of the passively embedded CRC code and that does not require surplusage multipliers or memory capacity.

SUMMARY OF THE INVENTION

The present invention is directed to a structure and method of implementing a direct comparison adaptive halt-

ing algorithm and decoder associated with iterative turbo decoding without resorting to use of a passively included CRC code. The soft output sequence observed at each iteration step contains information on three L-valued sequences; the channel information, the a priori information and the extrinsic information. The channel information sequence is constant during the iteration and thus does not have any information on the state of the convergence necessary to halt the iteration process. Thus, the change of the sum of the a priori information and the extrinsic information sequences is observed during each iteration step. The soft output sequence containing the channel information sequence is, however, referred to in order to estimate the state of the convergence, such as disclosed by Hagenauer et al. above. The sum of the a priori information sequence and the extrinsic information sequence contains accurate information on the state of the convergence and thus is quantized into a binary sequence. During an iteration, any changes of the binary sequence are detected. The iteration process is halted once this change can no longer be detected. The foregoing detection at each iteration step can be easily implemented by storing the reference sequence generated by a MAP decoder in each stage of a turbo decoder and updating the stored reference sequence for each stage following each iteration step, which does not seriously increase the hardware size of the decoder.

The present iterative turbo decoding process utilizing the direct comparison algorithm is implemented by dividing each iteration step into two stages. MAP-decoding is performed at each stage of the iteration step. The MAP-decoding produces information sequences at each stage that are then subsequently summed and quantized into binary sequences (reference sequences). The reference sequence at the second stage of one iteration step is stored in a memory location and then de-interleaved. The newly generated reference sequence at the first stage of the next iteration step is directly compared with the foregoing de-interleaved reference sequence and then interleaved. At the second stage of the iteration step, in the same way, the reference sequence generated at the second stage by the MAP decoder is directly compared with the foregoing interleaved reference sequence generated by the first stage MAP decoder. The iteration process is then halted only if the reference sequences at the first and the second stages of the iteration step correspond identically with those same reference sequences generated at the preceding iteration step. Thus, the direct comparison halting algorithmic turbo decoder estimates the state of the convergence in only one iteration step and thus can quickly determine the iteration step to be halted. The direct comparison halting algorithmic turbo decoder can halt the iteration earlier than CRC-based adaptive halting turbo decoders or such decoders otherwise requiring use of passively embedded CRC codes so that the computational complexity of the turbo decoder can be further reduced.

As used herein, the following words have the following meanings. The words "algorithmic software" mean an algorithmic program used to direct the processing of data by a computer or data processing device. The words "data processing device" as used herein refer to a CPU, DSP, microprocessor, micro-controller, or other like device and an interface system. The interface system provides access to the data processing device such that data could be entered and processed by the data processing device. The words "discrete data" as used herein are interchangeable with "digitized data" and "digitized data" as used herein means data which are stored in the form of singularly isolated, discontinuous data or digits. The word "interleaver" as used herein

means a single input, single output device that takes sequences of symbols in a fixed alphabet and produces an output sequence of the identical symbols over the same alphabet in a different temporal order. Then for an input sequence $x_i, i \in Z$ to an interleaver, the output sequence $y_1, i \in Z$ can be written as $y_1 = x_{\pi(i)}$, where π is defined as an invertible function: $\pi: Z \rightarrow Z$.

In one aspect of the invention, a method and associated structure are implemented to provide a direct comparison adaptive halting algorithm associated with iterative turbo decoding to more efficiently estimate the state of the convergence for a variable rate data communication signal.

In still another aspect of the invention, a method and associated structure are implemented to provide a direct comparison adaptive halting algorithm associated with iterative turbo decoding to estimate the state of the convergence of received communication signals devoid of passively embedded error detection, e.g. CRC, codes.

In yet another aspect of the invention, a method and associated structure are provided to implement a direct comparison adaptive halting algorithm associated with iterative turbo decoding to estimate the state of the convergence of a data communication signal without the necessity of direct reference to soft output sequences.

In another aspect of the invention, a method and associated structure are provided to implement a direct comparison adaptive halting algorithm associated with iterative turbo decoding to estimate the state of the convergence of a data communication signal without requiring either a large memory capacity or a multiplier with a long word length.

Another aspect of the invention is associated with a direct comparison adaptive halting algorithm iterative turbo decoding procedure and structure in which the computational complexity of the decoder(s) can be reduced by about 50% over known iterative turbo decoder structures without degradation in the BER and FER, to estimate the state of the convergence of a data communication signal.

Still another aspect of the invention is associated with a direct comparison adaptive halting algorithm for turbo decoding in which the computational complexity of the adaptive halting algorithm associated with a turbo decoder is substantially reduced in comparison with those CRC-based adaptive halting algorithms for turbo decoders known in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects and features of the present invention and many of the attendant advantages of the present invention will be readily appreciated as the same become better understood by reference to the following detailed description when considered in connection with the accompanying drawings in which like reference numerals designate like parts throughout the figures thereof and wherein:

FIG. 1 illustrates a turbo decoder structure suitable for implementing direct comparison adaptive halting algorithms devoid of CRC codes in accordance with one preferred embodiment of the present invention;

FIG. 2 is a flow diagram illustrating a direct comparison adaptive halting algorithm associated with the turbo decoder structure of FIG. 1, according to one preferred embodiment of the present invention;

FIG. 3(a) is a graph illustrating bit error rates (BER) and forward error rates (FER) for the present method and structure, a method and structure referring to the decoded sequence, and a method and structure using 8 iteration steps without adaptive halting;

FIG. 3(b) is a graph illustrating the average number of iteration steps to convergence for the present method and structure and a method and structure using 8 iteration steps without adaptive halting; and

FIG. 4 is a simplified block diagram of a parallel-concatenated turbo encoder for rate 1/3.

While the above-identified drawing figures set forth alternative embodiments, other embodiments of the present invention are also contemplated, as noted in the discussion. In all cases, this disclosure presents illustrated embodiments of the present invention by way of representation and not limitation. Numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and spirit of the principles of this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates a turbo decoder structure 100 suitable for implementing direct comparison adaptive halting algorithms in accordance with one preferred embodiment of the present invention. A rate 1/3 turbo coding associated with one systematic code sequence and two convolutional code sequences are considered herein to describe the present embodiments. The present invention is not so limited however, and it shall be understood that while a rate 1/3 turbo coding is considered herein, such rate is considered for illustration purposes only and to better explain a particular method and structure in accordance with one preferred embodiment of the present invention. The two convolutional code sequences are presumed to be generated in a transmitter (not shown), by convolving the input sequence and its interleaved sequence in parallel such that the output symbols are recursively determined. Generally, a decoder (discussed more fully below) receives the transmitted sequences as received sequences and re-constructs the original data source bit stream from the received data elements, which may have been corrupted by noise.

The present invention may be implemented in hardware or software, or a combination of both. In a preferred embodiment, the functions of a turbo decoder designed in conformance with the principals set forth herein are implemented as one or more integrated circuits using a suitable processing technology, e.g., CMOS.

As another example, the present invention may be implemented in computer programs, i.e. algorithms, executing on programmable computers each comprising a data processor, a data storage system, including both volatile and non-volatile memory and/or data storage devices, at least one input device, and at least one output device. Program code is applied to input data to perform the functions described herein and generate output information. The output information is applied to one or more output devices, in known fashion. Each such program may be implemented in a high level procedural or object oriented programming language to communicate with a computer system. However, the programs can be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language. Each such computer program is preferably stored on a storage media or device, e.g. ROM or magnetic disk) readable by a general or special purpose programmable computer, for configuring and operating the computer when the storage media or device is read by the computer to perform the procedures described herein. The inventive structure and methods may also be considered to be implemented as a computer-readable storage medium, configured with a computer program, where the storage

medium so configured causes a computer to operate in a specific and predefined manner to perform the functions described herein. An example of one such type of computer is a personal computer.

Looking again at FIG. 1, $X(k)$ represents the received noisy systematic sequence that contains the channel information. $Y(k)$ and $Y'(k)$ represent the two noisy convolutional code sequences corresponding to the input information sequence and its interleaved sequence respectively. The component k represents the time index for the symbol of the foregoing noisy sequences. The present method of turbo decoding is performed as iterative decoding in which each iteration step is further divided into two stages. Each of the two stages of iterative decoding is associated with a designated portion of the turbo decoder structure 100, e.g. portion containing MAP Dec. 1 decoder 106 using the a priori information sequence $L_{\text{apriori}}(k)$ 108 generated in the second stage of the preceding iteration step. This MAP-decoder 106 then generates the extrinsic information sequence $L_{\text{Extrinsic}}(k)$. The generated extrinsic information sequence $L_{\text{Extrinsic}}(k)$ is scaled via scaler 110 and interleaved via interleaver 112 to generate a new a priori information sequence for the second stage of the iteration step. The new a priori information sequence for the second stage of the iteration step as well as the interleaved channel information sequence $X'(k)$ and the convolutional code sequence $Y'(k)$ are then used in the MAP-Dec.2 decoder 114 to implement the MAP-decoding necessary to generate the extrinsic information sequence formulating the a priori information sequence in the following iteration step. The scaling factors α and β associated with scalers 110, 116 respectively, are changed at each iteration step using techniques familiar to those skilled in the art of iterative turbo decoding, and have values pre-optimized to speed up the convergence of the iterative decoding and to reduce the BER. These scaling factors are empirically determined and less than or equal to 1. A more detailed discussion of the scaling factors can be found in D. Divsalar and F. Pollara, On the Design of Turbo Codes, TDA Progress Report, 42:123, Jet Propulsion Lab., Pasadena, Calif., pp. 99-121, November, 1995 and the Berrou et al. reference discussed herein above. Both references are incorporated by reference herein. Further, scaling factors of 1.0 generally achieve sufficiently good BER performance if the MAP decoder(s) is implemented by the full algorithm disclosed in L. R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, Optimal Decoding of Linear Codes for Minimizing Symbol Error Rate, IEEE Trans. Inf. Theory, vol. IT-20, pp. 284-287, March, 1974, incorporated by reference herein. However, Berrou et al. have shown that when a large number of iterations are carried out, the scaling factors are often given as values slightly less than 1.0, i.e. 0.98. Scaling factors less than 1.0 are effective to reduce bit error rates, especially for the Max Log-MAP algorithm, the soft output Viterbi algorithm and the like. Unless the scaling factors have values far smaller or larger than 1.0, turbo decoders keep BER performance without degradation; and halting criteria for the turbo decoding do not degrade the BER performance.

A discussion directed to MAP-decoders, the a priori information sequence and the extrinsic information sequence are immediately set forth herein below to provide additional background directed to a better understanding the instant embodiment of the present invention. First, the log

likelihood ratio $L(X)$ for a random variable $X \in \{1, -1\}$ is defined as

$$L(X) = \log \frac{P(X = +1)}{P(X = -1)}, \quad 1)$$

in agreement with Hagenauer et al., where $P(X=\pm 1)$ denotes the probability that the random variable X takes on the values $+1$ and -1 , respectively. Then using

$$P(X=+1)+P(X=-1)=1, \quad 2)$$

$$P(X = \pm 1) = \frac{e^{\pm L(X)}}{1 + e^{\pm L(X)}}. \quad 3)$$

Further, a rate 1/2 systematic convolutional code is now also used as an example. An information sequence is then defined as $u=[u_1, u_2, \dots, u_N]$, $u_k \in \{1, -1\}$ for $k=1, \dots, N$, and a corresponding code word vector is defined as $c(u)=[c_1(u), c_2(u), \dots, c_{2N}(u)]$, $c_n(u) \in \{1, -1\}$ for $n=1, \dots, 2N$. The set of all possible information sequences is further identified as U and an observation vector of the code word through an AWGN channel corresponding to the information sequence is defined as $v=[v_1, v_2, \dots, v_{2N}]$. The MAP decoder has two inputs, i.e. the apriori information sequence and the observation vector, and two outputs, i.e. the soft output sequence and the extrinsic information sequence. The apriori information sequence $L_{apriori}(k)$ for $k=1, \dots, N$ is defined as the scaled extrinsic information sequence which is one of the previous outputs of the MAP decoder of the turbo decoder. Then by using a given apriori information sequence and observation, the MAP decoder computes the soft output sequence and the extrinsic information sequence. The soft output sequence is defined as

$$L_{SoftOut}(k) = \log \frac{\sum_{u \in U, u_k=+1} \left(\prod_{j=1}^{2N} p(v_j | c_j(u)) \prod_{j=1}^N P(u_j) \right)}{\sum_{u \in U, u_k=-1} \left(\prod_{j=1}^{2N} p(v_j | c_j(u)) \prod_{j=1}^N P(u_j) \right)}, \quad 4)$$

where

$$P(u_j = \pm 1) = \frac{e^{\pm L_{apriori}(j)}}{1 + e^{\pm L_{apriori}(j)}} \text{ and}$$

$$p(v_j | c_j(u)) = \frac{1}{\sqrt{\pi N_0}} e^{-\frac{(v_j - c_j(u))^2}{N_0}}.$$

Note that E_s of the observation vector is assumed to be 1.0. Further, $v_{n'}$ is defined to be the observation of the systematic code bit $c_{n'}(u)$ corresponding to the information bit u_k . The extrinsic information sequence is then defined as

$$L_{Extrinsic}(k) = L_{SoftOut}(k) - L_{apriori}(k) - X(k), \quad 7)$$

where

$$X(k) = \log \frac{\exp\left(-\frac{(v_{n'} - 1)^2}{N_0}\right)}{\exp\left(-\frac{(v_{n'} - 1)^2}{N_0}\right)} = \frac{4}{N_0} v_{n'}.$$

The extrinsic information sequence is then scaled, interleaved and used as the apriori information sequence in the

next MAP decoding. The scaling factor is generally equal to or slightly less than 1, as discussed herein before.

The soft output sequence, e.g. $L_{SoftOut}(k)$ 118, associated with either stage of each iteration step can be seen to be produced by adding the three sequences; the a priori information sequence, the channel information sequence and the extrinsic information sequence. Each soft output sequence, e.g. $L_{SoftOut}(k)$ 118, is quantized into one bit via a respective quantizer 124, 126, to generate a binary sequence that corresponds to the decoded sequence in the associated stage of the iteration step. The decoded sequence in the second stage can be seen to be obtained by de-interleaving the quantized soft output sequence via a De-Interleaver 128 to account for the channel information sequence passing through Interleaver 130.

During the iteration taking place in the above described adaptive halting turbo decoding process, the amplitude of the above described soft output gradually becomes larger; and the decoded sequence often becomes error-free after a few iteration steps. The decoded sequence therefore does not change by further iteration once the decoded sequence becomes error-free. Thus, the error-free decoded sequence can be detected simply by detecting when the decoded sequence is identical to one at the preceding iteration step. Such error-free detection techniques have limitations however. For example, it is known that even the decoded sequence with errors is often unchanged through several successive iteration steps, especially in the case of turbo decoding associated with finite word length arithmetic. Application of the foregoing error-free detection technique in such circumstances would likely halt the iteration process too early, seriously degrading the BER. In view of the foregoing limitations associated with known turbo decoding structures and methods, it is important to also be able to estimate the state of the convergence during the iterative decoding process. The decoded bits 132, 134 can be seen to be generated by quantizing the soft output $L_{SoftOut}(k)$ shown as

$$L_{SoftOut}(k) = X(k) + L_{apriori}(k) + L_{Extrinsic}(k), \quad (9)$$

The soft output $L_{SoftOut}(k)$ sequence thus comprises three information sequences, the a priori, the extrinsic and the channel information. The channel information sequence $X(k)$ is constant during the iteration process, and thus has no information on the state of the convergence. The sequence comprising $L_{apriori}(k) + L_{Extrinsic}(k)$ is therefore more informative on the state of the convergence than the soft output sequence.

The turbo decoder structure 100 can be seen to also generate the above described information sequence comprising $L_{apriori}(k) + L_{Extrinsic}(k)$ at each stage of the turbo decoder structure 100. These information sequences comprising $L_{apriori}(k) + L_{Extrinsic}(k)$ are subsequently quantized via quantizers 120 and 122 respectively to formulate binary sequences (quantized reference sequences). These quantized reference sequences at the first and second stages of the turbo decoder structure 100 and generated during an iteration step are compared with the respective reference sequences generated during a preceding iteration step. The iteration process is halted once the quantized reference sequences generated at the iteration step are identical to those generated at the preceding iteration step. The present direct comparison adaptive halting algorithm is achieved via the turbo decoder structure 100 to estimate the state of the convergence to halt the iteration process, even if the transmitted sequences are not encoded with error-detection codes. Since the present adaptive halting technique associ-

ated with the two stages of the turbo decoder structure 100 does not directly refer to the soft output sequences having long word lengths as the halting criteria, the necessity for a large memory to accommodate storage of the soft output sequences or a multiplier having long word lengths is negated. The present invention therefore possesses characteristics that are advantageous over known adaptive halting techniques and structures. With continued reference to FIG. 1, the reference sequence at the second stage of one iteration step is stored in a first memory location. The memory location can be a storage register within any suitable memory device, e.g. existing turbo encoder memory, storage registers or cells associated with a comparator element and the like. The reference sequence is next de-interleaved in De-Interleaver 136. At the first stage of the next iteration step, the newly generated reference sequence is directly compared with the foregoing de-interleaved reference sequence via Comparator 140 and then interleaved in Interleaver 138. At the second stage of the iteration step, in the same way, the reference sequence generated by the MAP Dec. 2 decoder 114 is directly compared with the interleaved reference sequence generated by the MAP Dec. 1 decoder 106. Then, if any change of the reference sequence is not detected in the two comparisons, the iteration process is halted.

The present method then, represents a significant advancement in the state of present art associated with adaptive halting algorithms and iterative turbo decoding structures and methods. The hardware size requirements associated with the present direct comparison adaptive halting turbo decoder structure 100, e.g. decoders, comparators, registers and the like, are substantially insignificant in comparison with the MAP decoders and interleavers associated with known turbo decoders. Extra memory however, is required to store the binary reference sequence. Since the turbo decoder 100 itself requires rather large memory requirements in order to store the received sequence and also the intermediate extrinsic information sequence, the addition of the far smaller memory required to store the binary reference sequence does not render any type of serious problem in practical applications.

FIG. 2 is a flow diagram illustrating the above described direct comparison adaptive halting algorithm 200 associated with the turbo decoder structure 100 of FIG. 1, according to one preferred embodiment of the present invention. The scaling operations have been omitted to preserve simplicity of explanation. The sum of the a priori information sequence $L_{\text{apriori}}(k)$ and the extrinsic information sequence $L_{\text{Extrinsic}}(k)$ is seen to be computed at each iteration step. Since the sum sequence is sufficiently informative on the state of the convergence, it can be quantized into a binary sequence and observed for changes during the iteration. The iteration is then halted when there is no longer any detectable change in the binary sequence during two concatenated iteration steps.

FIG. 3(a) is a graph illustrating bit error rates (BER) and forward error rates (FER) for 1) the present direct comparison adaptive halting method and structure, 2) a method and structure referring to the decoded sequence, and 3) a method and structure using 8 iteration steps without adaptive halting. The effectiveness of the present structure and method can be demonstrated by simply comparing the present structure and method with a turbo decoder using the adaptive halting algorithm in which the decoded sequence, rather than the reference sequence, is used for the halting criterion. The decoded sequence is obtained first by quantizing the soft output sequence into a binary sequence such as discussed herein above. Changes in the decoded sequence are detected

by the passively embedded CRC code during the iteration, also discussed above. The above comparison used a CRC code generated via a polynomial generator common to both the present CRC-based technique and the decoded sequence technique. The polynomial generator is represented by equation (10) below.

$$x^{32}+x^{26}+x^{23}+x^{22}+x^{16}+x^{12}+x^{11}+x^{10}+x^8+x^7+x^5+x^4+x^2+1 \quad (10)$$

Further, the rate 1/3 turbo code disclosed in *3rd Generation Partnership Project (3GPP) Technical Specification*, Physical Layer General Description, June 1999, was used in the instant comparison. The MAP-decoding in the turbo decoder was accomplished using a finite word length via application of the Max-Log MAP algorithm disclosed by Robertson et al. in A Comparison of Optimal and Sub-optimal MAP Decoding Algorithms Operating in the Log Domain, Proc. ICC'95, pp. 1009-1013, June 1995. The Robertson et al. reference and the '3GPP' reference are incorporated by reference herein. The received signals $X(k)$, $Y(k)$ and $Y'(k)$ were scaled and quantized into 6 bit symbols. The extrinsic information symbols and the state metrics were quantized into 9 bit symbols within the present direct comparison adaptive halting turbo decoder and then stored in memory. The scaling factors α and β , having finite word lengths, were changed at each iteration step with pre-optimized values to accommodate fast convergence of the iterative decoding such as discussed above. The physical layer disclosed in the *3rd Generation Partnership Project (3GPP) Technical Specification* referenced above was used to formulate a turbo encoder with eight states and an interleaver having a variable symbol length between 320 and 5120 bits. The interleaver for the above comparison had a symbol length of 1171 bits. The foregoing parameters were then used to evaluate the BER and FER of the decoder outputs at several E_b/N_0 's of the additive white gaussian noise channel.

The adaptive haltings via the present direct comparison adaptive halting algorithm can be seen to significantly reduce the BER and FER of the above decoder when contrasted with application of the above described decoded sequence adaptive halting algorithm. The BER and FER associated with the decoded sequence adaptive halting algorithm are seriously degraded since they have a high E_b/N_0 error floor. This degradation is caused due to the fact that the decoded sequence is not as informative on the state of the convergence since the decoded sequence also includes the channel information sequence that is constant during the iteration process as discussed herein before. The reference sequence, defined as the quantized version of $L_{\text{apriori}}(k)+L_{\text{Extrinsic}}(k)$, is therefore seen as sufficient to know the state of the convergence. The foregoing application of adaptive halting algorithms applied to a turbo decoder further confirms that the reference sequence can thus be utilized to accurately estimate the state of the convergence using the present direct comparison adaptive halting techniques.

FIG. 3(b) is a graph illustrating the average number of iteration steps to convergence for 1) the present method and structure and 2) a method and structure using 8 iteration steps without adaptive halting. The adaptive haltings via the direct comparison adaptive halting algorithm can be seen to significantly reduce the average number of iteration steps without causing degradation in the BER and/or FER when compared with a decoder configured to complete 8 full iteration steps. A closer look at FIG. 3(b) shows that the direct comparison adaptive halting decoder completed its decoding process in about 4 iteration steps at $E_b/N_0=1.2$ dB. Since the 8-step decoder completed its decoding process in 8 iteration steps at $E_b/N_0=1.2$ dB, the present direct com-

parison adaptive halting decoder can be seen to require only 50% of the computational complexity of the 8-step adaptive halting decoder.

In summary explanation of the above, the present invention can accurately estimate the state of the convergence for transmitted sequences received and processed by an adaptive halting turbo decoder, even when the transmitted sequences are not encoded with error-detection codes. Because the present invention does not directly refer to any soft output sequences, memory capacity requirements are not wasted to accommodate storage of soft output sequences having long word lengths or multipliers having long word lengths. This is a substantial advantage over known structure and techniques associated with adaptive halting algorithms for iterative turbo decoding.

This invention has been described in considerable detail in order to provide those skilled in the equalizer art with the information needed to apply the novel principles and to construct and use such specialized components as are required. In view of the foregoing descriptions, it should be apparent that the present invention represents a significant departure from the prior art in construction and operation. However, while particular embodiments of the present invention have been described herein in detail, it is to be understood that various alterations, modifications and substitutions can be made therein without departing in any way from the spirit and scope of the present invention, as defined in the claims which follow. For example, although various embodiments have been presented herein with reference to particular turbo decoder elements and associated characteristics, the present inventive structures and methods are not necessarily limited to a particular turbo decoder architecture or set of characteristics as used herein. Depending upon the particular application, a decoder element can mean a single element or any combination of decoder elements, so long as the present direct comparison adaptive halting can be preserved.

What is claimed is:

1. A method of iteratively decoding a sequence of received signals, representative of systematic convolutional encoded elements generated by a parallel-concatenated encoder from a source of original digital data elements, into decoded elements corresponding to the original digital data elements, the method comprising the steps of:

- (a) applying a received input information sequence $X(k)$, a first received convolutional code sequence $Y(k)$ corresponding to the input information sequence, and a first a priori information sequence to a first probability-based decoder to generate a first extrinsic information sequence;
- (b) applying an interleaved received input information sequence $X'(k)$, a second received convolutional code sequence $Y'(k)$ corresponding to the interleaved input information sequence, and a second a priori information sequence to a second probability-based decoder to generate a second extrinsic information sequence;
- (c) applying the first a priori information sequence and the first extrinsic information sequence to a first combinatorial element to generate a first reference sequence;
- (d) applying the first reference sequence to a first quantizer to generate a first quantized reference sequence;
- (e) applying the second a priori information sequence and the second extrinsic information sequence to a second combinatorial element to generate a second reference sequence;
- (f) applying the second reference sequence to a second quantizer to generate a second quantized reference sequence;

- (g) applying the first quantized reference sequence to a first interleaver to generate an interleaved first quantized reference sequence;
- (h) applying the first quantized reference sequence to a first comparator element;
- (i) applying the interleaved first quantized reference sequence to a second comparator element;
- (j) storing the second quantized reference sequence in a data storage location;
- (k) applying the second quantized reference sequence to the second comparator element;
- (l) applying the second quantized reference sequence to a first de-interleaver element to generate a de-interleaved second quantized reference sequence;
- (m) applying the de-interleaved second quantized reference sequence to the first comparator element;
- (n) comparing the de-interleaved second quantized reference sequence with the first quantized reference sequence within the first comparator element;
- (o) comparing the interleaved first quantized reference sequence with the second quantized reference sequence within the second comparator element;
- (p) repeating steps (a) through (o) until the compared signals within the first and second comparator elements are identical; and
- (q) generating substantially error-free decoded elements when the compared signals within the first and second comparator elements are identical.

2. The method of iteratively decoding a sequence of received signals according to claim 1 further comprising the step of applying the first extrinsic information sequence to a first scaler and a first interleaver to generate the second a priori information sequence.

3. The method of iteratively decoding a sequence of received signals according to claim 1 further comprising the step of applying the second extrinsic information sequence to a second scaler and a second de-interleaver to generate the first a priori information sequence.

4. The method of iteratively decoding a sequence of received signals according to claim 1 wherein the step (q) of generating substantially error-free decoded elements when the compared signals within the first and second comparator elements are identical comprises the step of applying the received input information sequence $X(k)$ and the first reference sequence to a third combinatorial element and a third quantizer to generate a first SoftOut information sequence.

5. The method of iteratively decoding a sequence of received signals according to claim 4 wherein the step (q) of generating substantially error-free decoded elements when the compared signals within the first and second comparator elements are identical further comprises the step of applying the interleaved received input information sequence $X'(k)$ and the second reference sequence to a fourth combinatorial element and a fourth quantizer to generate a second SoftOut information sequence.

6. The method of iteratively decoding a sequence of received signals according to claim 1 wherein the step (p) of repeating steps (a) through (o) comprises the step of applying the generated first extrinsic information sequence to a first pre-optimized scaler element such that the first pre-optimized scaler element is capable of rescaling the generated first extrinsic information sequence during each iteration step to generate a new first extrinsic information sequence.

7. The method of iteratively decoding a sequence of received signals according to claim 6 wherein the step (p) of repeating steps (a) through (o) further comprises the step of applying the generated second extrinsic information sequence to a second pre-optimized scaler element such that the second pre-optimized scaler element is capable of rescaling the generated second extrinsic information sequence during each iteration step to generate a new second extrinsic information sequence.

8. A method of iteratively decoding a sequence of received signals, representative of systematic convolutional encoded elements generated by a parallel-concatenated encoder from a source of original digital data elements, into decoded elements corresponding to the original digital data elements, the method comprising the steps of:

- (a) providing a pair of decoder modules, each decoder module having a pair of received signal inputs, a feedback input, and an output, such that the output of each decoder module is coupled to the feedback input of each other decoder module;
- (b) applying a non-interleaved received signal sequence to the received signal inputs of one decoder module and an interleaved received signal sequence to the received signal inputs of the other decoder module, such that each decoder module generates an output sequence;
- (c) combining a feedback information sequence applied to each decoder module feedback input with its respective generated output sequence to provide a quantized reference sequence associated with each decoder module;
- (d) applying 1) a quantized reference sequence associated with the decoder module receiving an interleaved signal sequence and 2) an interleaved quantized reference sequence associated with the decoder module receiving a non-interleaved signal sequence to a second comparator element;
- (e) applying 1) a quantized reference sequence associated with the decoder module receiving a non-interleaved signal sequence and 2) a de-interleaved quantized reference sequence associated with the decoder module receiving an interleaved signal sequence to a first comparator element; and
- (f) generating substantially error-free decoded elements when the compared signals within each comparator are identical.

9. The method of iteratively decoding a sequence of received signals according to claim 8 wherein the step (c) of combining a feedback information sequence applied to each decoder module feedback input with its respective generated output sequence to provide a quantized reference sequence associated with each decoder module further comprises the step of scaling the generated output of each decoder via a distinct adaptive scaler element associated with each decoder to generate a new feedback information sequence associated with each decoder.

10. The method of iteratively decoding a sequence of received signals according to claim 8 wherein the step (f) of generating substantially error-free decoded elements when the compared signals within each comparator are identical comprises the step of applying the combined received signal sequence, feedback information sequence and generated output sequence associated with one of the decoder modules to a combinatorial element and a quantizer to generate a first decoded bit stream.

11. The method of iteratively decoding a sequence of received signals according to claim 10 wherein the step of generating substantially error-free decoded elements when

the compared signals within each comparator are identical further comprises the step of applying the combined interleaved received signal sequence, feedback information sequence and generated output sequence associated with the other decoder module to a combinatorial element and quantizer to generate a second decoded bit stream.

12. The method of iteratively decoding a sequence of received signals according to claim 8 wherein the step (c) of combining a feedback information sequence applied to each decoder module feedback input with its respective generated output sequence comprises the step of applying the combined feedback information sequence and generated output sequence associated with each decoder module to a combinatorial element and quantizer associated with each decoder module respectively.

13. A direct comparison adaptive halting turbo decoder comprising:

- a first probability-based decoder having at least two received signal inputs, a feedback signal input and a signal output, the first probability-based decoder configured to receive an input information sequence and a convolved input information sequence;
 - a second probability-based decoder having at least two received signal inputs, a feedback signal input and a signal output, such that the first probability-based decoder signal output is coupled to the second probability-based decoder feedback signal input, and further such that the second probability-based decoder signal output is coupled to the first probability-based decoder feedback signal input, the second probability-based decoder configured to receive an interleaved input information sequence and an interleaved convolved input information sequence;
 - a first combinatorial element coupled to the first probability-based decoder and configured to generate a first reference sequence comprising a feedback information sequence and an output information sequence, both associated with the first probability-based decoder;
 - a second combinatorial element coupled to the second probability-based decoder and configured to generate a second reference sequence comprising a feedback information sequence and an output information sequence, both associated with the second probability-based decoder;
 - a first quantizer configured to receive the first reference sequence and generate a first quantized reference sequence;
 - a first interleaver configured to receive the first reference sequence and generate an interleaved first quantized reference sequence;
 - a second quantizer configured to receive the second reference sequence and generate a second quantized reference sequence;
 - a first de-interleaver configured to receive the second quantized reference sequence and generate a de-interleaved second quantized reference sequence;
 - a first comparator configured to receive the first quantized reference sequence and the de-interleaved second quantized reference sequence; and
 - a second comparator configured to receive the second quantized reference sequence and the interleaved first quantized reference sequence.
14. The direct comparison adaptive halting turbo decoder according to claim 13 further comprising a first scaler

element coupled to the signal output of the first probability-based decoder and configured to scale a feedback signal to the second probability-based decoder.

15. The direct comparison adaptive halting turbo decoder according to claim 13 further comprising a second scaler element coupled to the signal output of the second probability-based decoder and configured to scale a feedback signal to the first probability-based decoder. 5

16. The direct comparison adaptive halting turbo decoder according to claim 13 further comprising a third combinatorial element coupled to the first combinatorial element and the first quantizer. 10

17. The direct comparison adaptive halting turbo decoder according to claim 16 further comprising a fourth combinatorial element coupled to the second combinatorial element and the second quantizer. 15

18. The direct comparison adaptive halting turbo decoder according to claim 17 further comprising a third quantizer coupled to the third combinatorial element to generate a first decoded bit sequence comprising the input information sequence. 20

19. The direct comparison adaptive halting turbo decoder according to claim 18 further comprising a fourth quantizer coupled to the fourth combinatorial element to generate a second decoded bit sequence comprising the input information sequence. 25

20. A direct comparison adaptive halting turbo decoder comprising:

- a first probability-based MAP decoder having two received signal inputs, a feedback input and an output;
- a second probability-based MAP decoder having two received signal inputs, a feedback input and an output;
- a first scaler element having an output and further having an input coupled to the output of the first probability-based MAP decoder;

- a first interleaver having an input coupled to the output of the first scaler and further having an output coupled to the feedback input of the second probability-based MAP decoder;

- a second scaler element having an output and further having an input coupled to the output of the second probability-based MAP decoder;

- a first de-interleaver having an input coupled to the output of the second scaler element and further having an output coupled to the feedback input of the first probability-based MAP decoder;

- a first combinatorial element having an output and further having a first input coupled to the feedback input of the first probability-based MAP decoder and further having a second input coupled to the output of the first probability-based MAP decoder;

- a second combinatorial element having an output and further having a first input coupled to the feedback input of the second probability-based MAP decoder and further having a second input coupled to the output of the second probability-based MAP decoder; 55

- a first quantizer having an input coupled to the output of the first combinatorial element and further having an output;

- a second quantizer having an input coupled to the output of the second combinatorial element and further having an output;

- a first comparator having a first input coupled to the output of the first quantizer and further having a second input and an output; 60

a second comparator having an input coupled to the output of the second quantizer and further having an output;

a second interleaver having a first input coupled to the output of the first quantizer and further having an output;

a second comparator having a first input coupled to the output of the second interleaver, a second input coupled to the output of the second quantizer and further having an output; and

a second de-interleaver having an input coupled to the output of the second quantizer and having an output coupled to the second input of the first comparator. 15

21. The direct comparison adaptive halting turbo decoder of claim 20 further comprising a first storage unit configured to store a quantized reference sequence associated with the second quantizer.

22. The direct comparison adaptive halting turbo decoder of claim 21 further comprising a second storage unit configured to store a quantized reference sequence associated with the first quantizer.

23. The direct comparison adaptive halting turbo decoder of claim 22 further comprising a third combinatorial element having a first input coupled to the output of the first combinatorial element and further having a second input coupled to a received signal input of the first probability-based decoder. 25

24. The direct comparison adaptive halting turbo decoder of claim 23 further comprising a fourth combinatorial element having a first input coupled to the output of the second combinatorial element and further having a second input coupled to a received signal input of the second probability-based decoder. 30

25. The direct comparison adaptive halting turbo decoder of claim 24 further comprising a third quantizer having an input coupled to the output of the third combinatorial element and further having an output. 35

26. The direct comparison adaptive halting turbo decoder of claim 25 further comprising a fourth quantizer having an input coupled to the output of the fourth combinatorial element and further having an output. 40

27. The direct comparison adaptive halting turbo decoder of claim 26 further comprising a third de-interleaver having an input coupled to the output of the fourth quantizer and further having an output. 45

28. A direct comparison adaptive halting decoder, comprising

- a turbo decoder configured to receive an input information sequence, a convolved input information sequence and an interleaved convolved input information sequence;

- a pair of comparators, each comparator coupled to a distinct one of the turbo decoders and configured to generate decoded halting sequences, the decoded halting sequences associated with sum sequence information comprising solely of a priori and extrinsic sequence information, the decoded halting sequences generated without direct reference to soft output sequence information.

29. The direct comparison adaptive halting decoder according to claim 28 wherein the turbo decoder is further configured to determine a change in the sum sequence information associated with contiguous iterations. 60

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